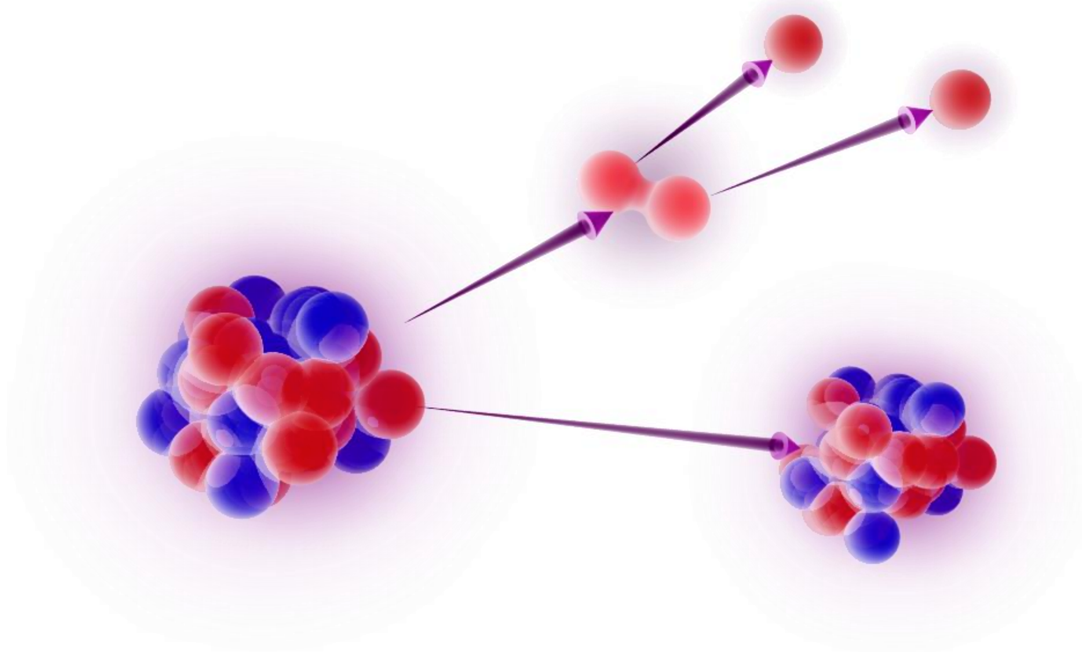
2-proton radioactivity: opportunities at FAIR

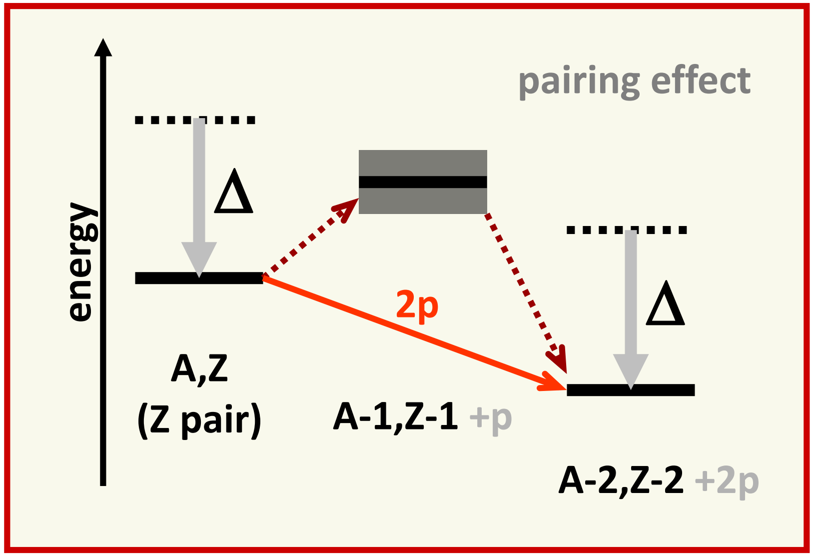
J. Giovinazzo

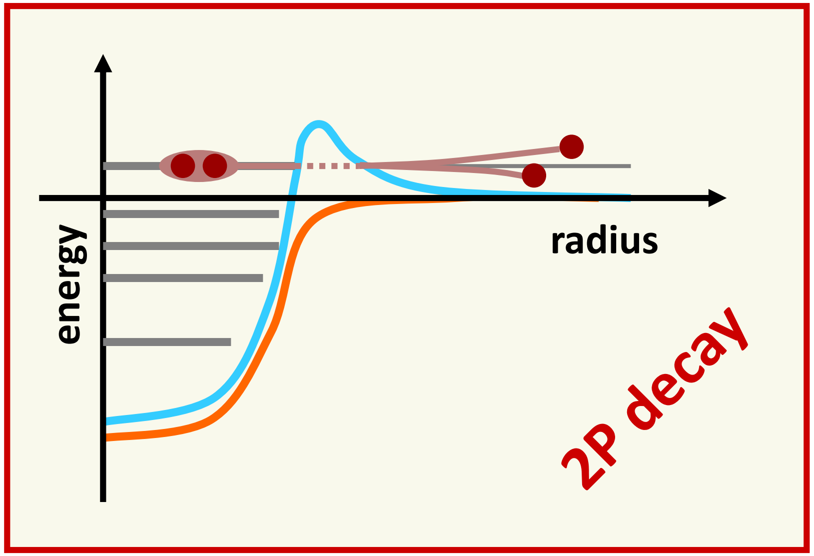
CENBG



- 2P radioactivity
- scientific interest
- experimental search
- further studies
- possibilities with FAIR

▶ ground-state 2-proton radioactivity

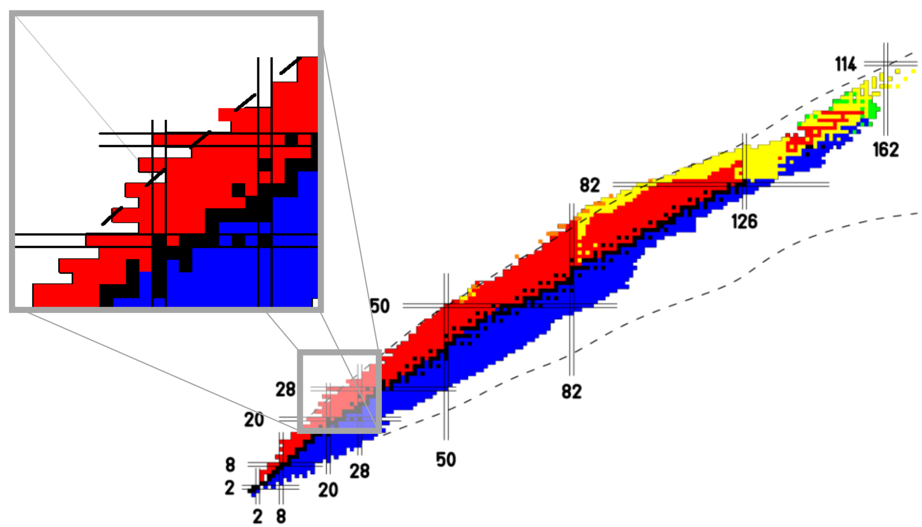




- **even Z** (pairing)
- **unbound protons** (tunnel effect)

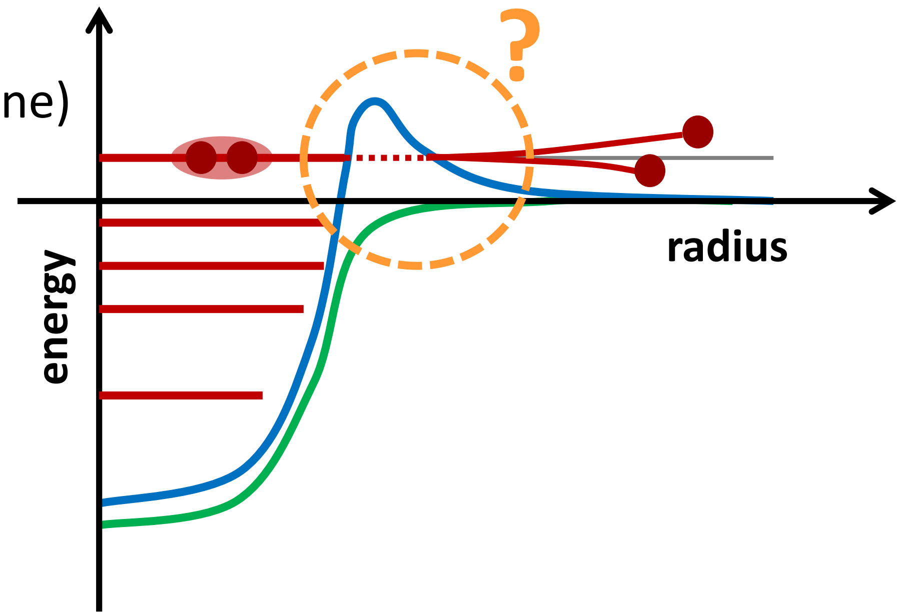
- 1-proton emission forbidden
- simultaneous / correlated emission

- **proposed in 1960**
  V.I. Goldanski
- **observed in 2002**
  @ GANIL & GSI → fragmentation



scientific motivation

- **drip-line and masses** (beyond the drip-line)
  transition Q-values
- **nuclear structure**
  energy, half-life, levels configurations
- **pairing**
  correlation of emitted protons
- **tunnel effect**
  theoretical description



the emitted protons carry information on what's going on inside the nucleus
the 2-proton radioactivity mixes the **structure** (wave functions) and the (decay) **dynamics**

▶ scientific motivation

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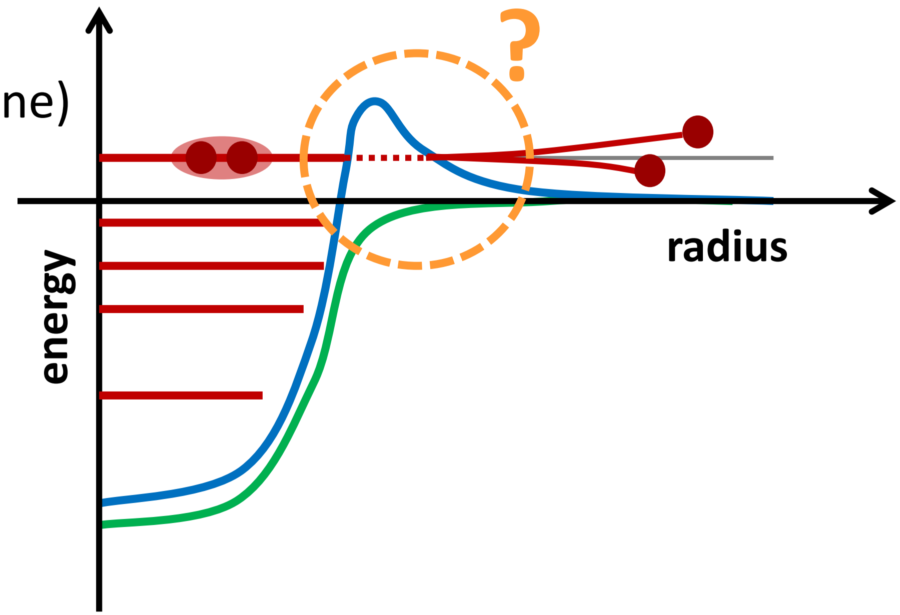

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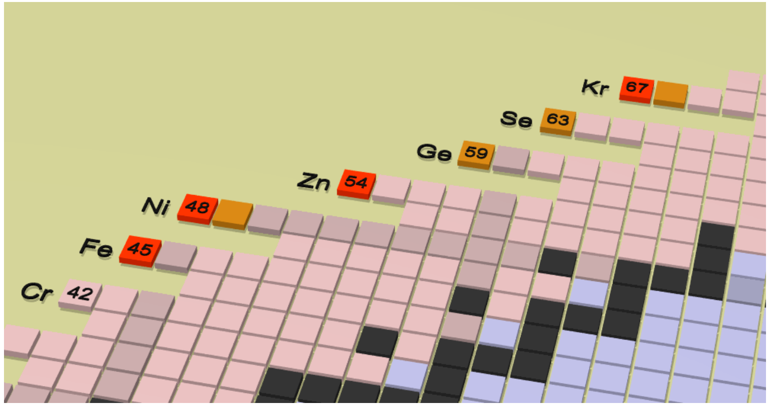
the 2-proton radioactivity mixes the **structure** (wave functions) and the (decay) **dynamics**

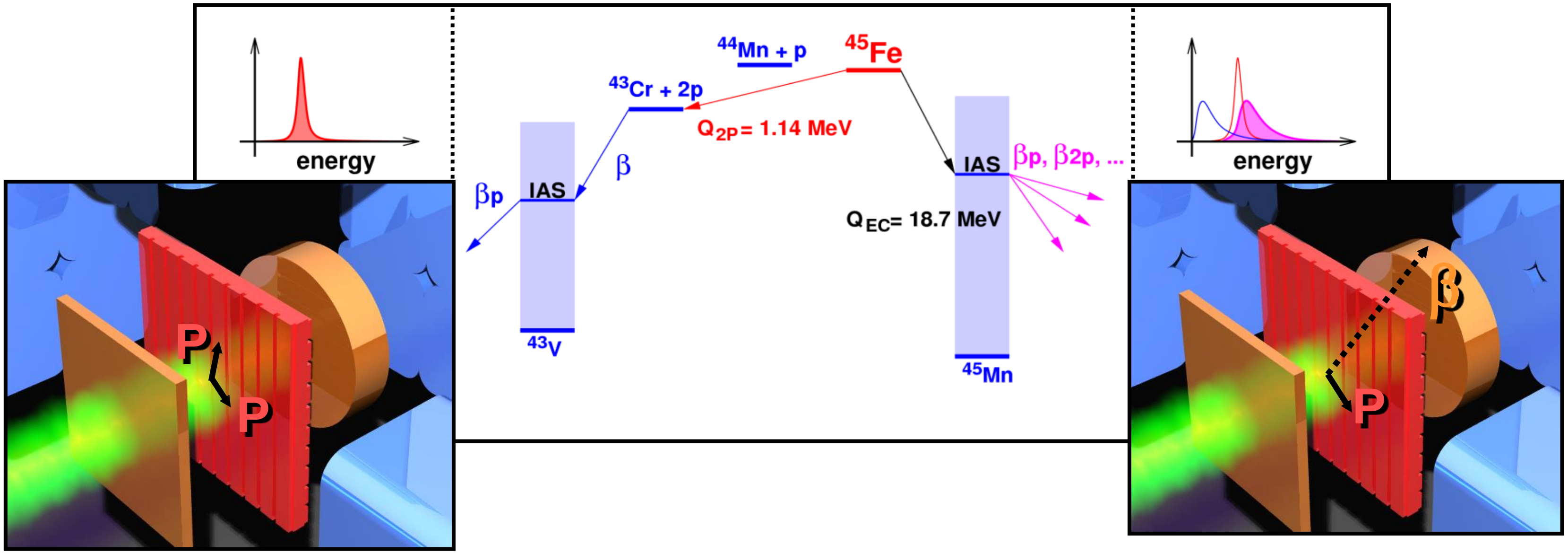


▶ ▶ even-Z drip-line nuclei

- **only at fragmentation facilities !!!**
- **GANIL/LISE** (^{45}Fe , ^{48}Ni, ^{54}Zn), **GSI/FRS** (^{45}Fe), **NSCL/A1900** (^{45}Fe, ^{48}Ni), **RIKEN/BigRIPS** (^{67}Kr)
- **FAIR…**

▶ discovery experiments: indirect observation

- **projectile fragmentation experiments**
- **implantation-decay technique in silicon telescope** (standard DSSD devices)
  limited decay information: **energy**, **half-life** (& **daughter decay**), **branching ratio**

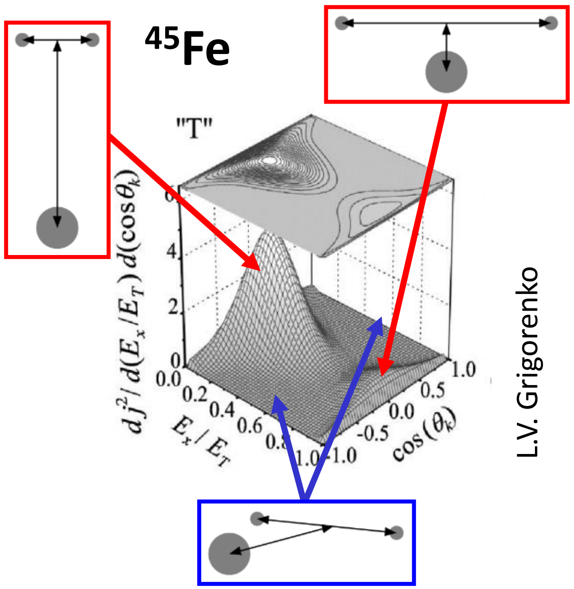


- isotopes discovery: ^{45}Fe (GSI 1996), ^{48}Ni (GANIL 1999) – no decay data

- **indirect signature of 2P emitters** (no information about individual protons)
  - ▷ **first observation: ^{45}Fe** (**GANIL** 2002, **GSI** 2002)
  - ▷ **other emitters ^{54}Zn** (**GANIL** 2005), (^{48}Ni (GANIL 2005) ?)
  - ▷ **recent result: ^{45}Fe (RIKEN** 2016)

correlation studies: tracking experiments

- **proton-proton correlations measurement**
  (3-body model) – angle & energy → emission process
  → wave functions orbitals



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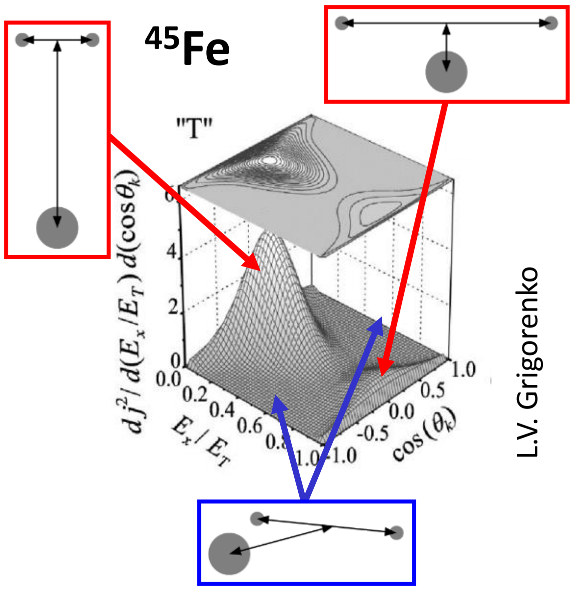
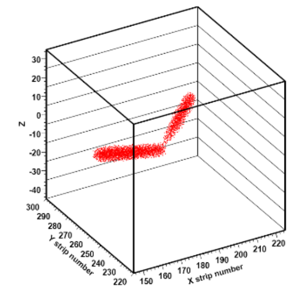
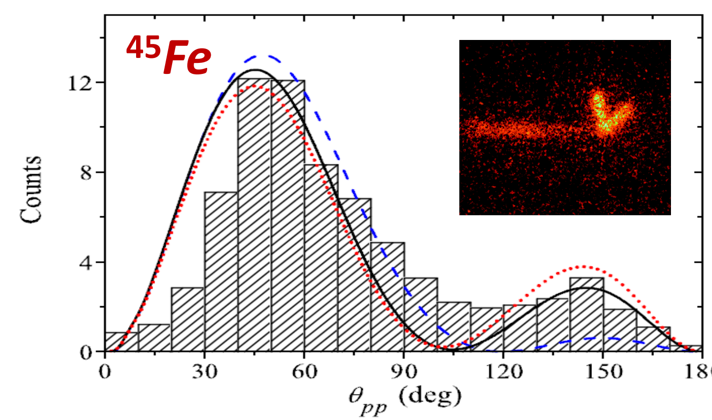




L.V. Grigorenko

- **development of TPCs**
  - CENBG TPC
    ^{45}Fe: **first direct observation** (GANIL 2006)
    ^{54}Zn: few events (GANIL 2008)
  - Warsaw Optical TPC
    ^{45}Fe: **angular distribution** (NSCL 2009)
    ^{48}Ni: few events (NSCL 2011)



K. Miernik *et al.*, PRL 2009

▶ correlation studies: tracking experiments

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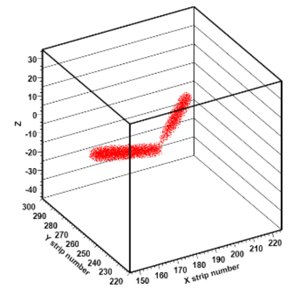

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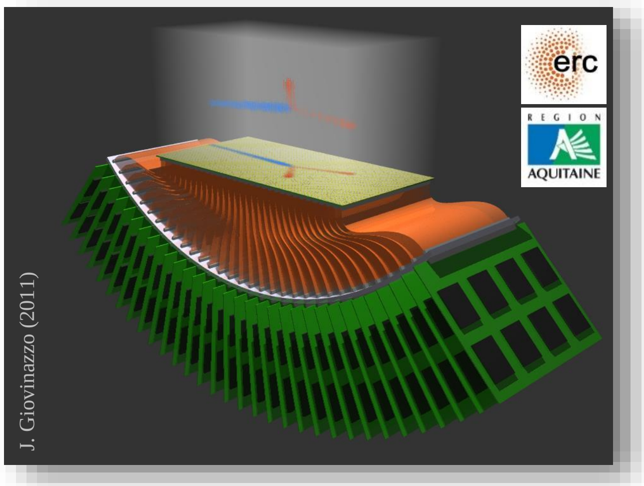
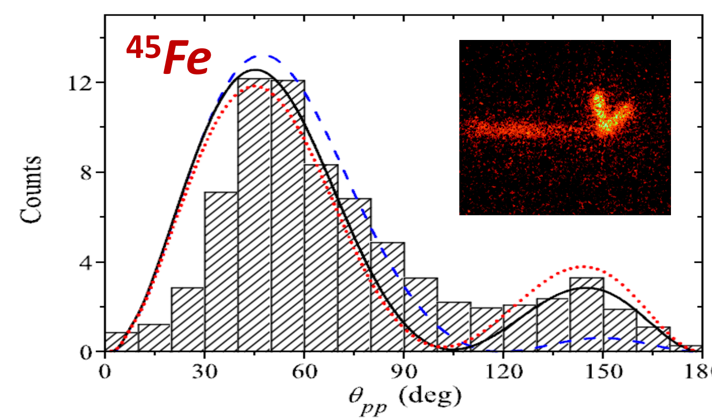


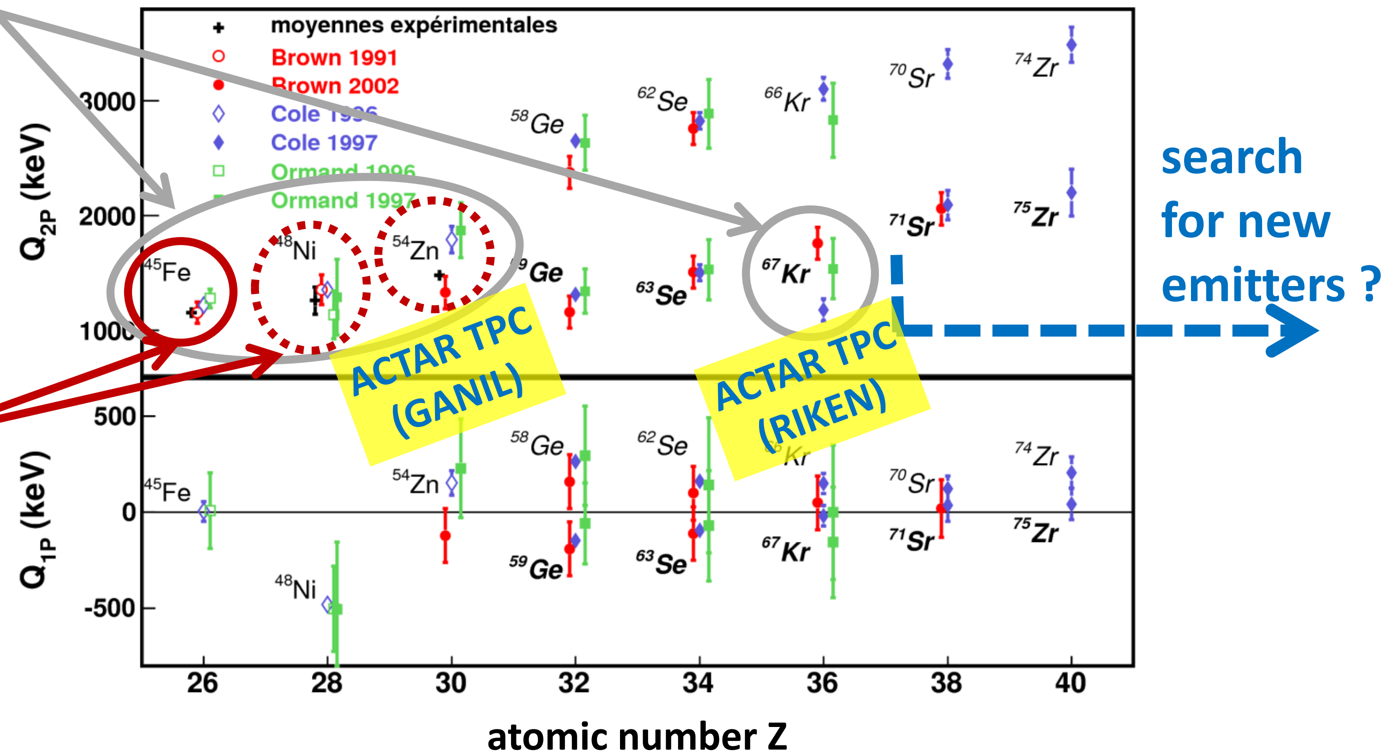
- **new device: ACTAR TPC**
  designed for **RIKEN** & **FAIR** energies
  accepted experiments (2018-2019 ?)
  ▷ **^{48}Ni/ ^{54}Zn** @ **GANIL/LISE**
  ▷ **^{67}Kr** @ **RIKEN/BigRIPS**



K. Miernik *et al.*, EPJA (2007)

experimental status

- **known cases**



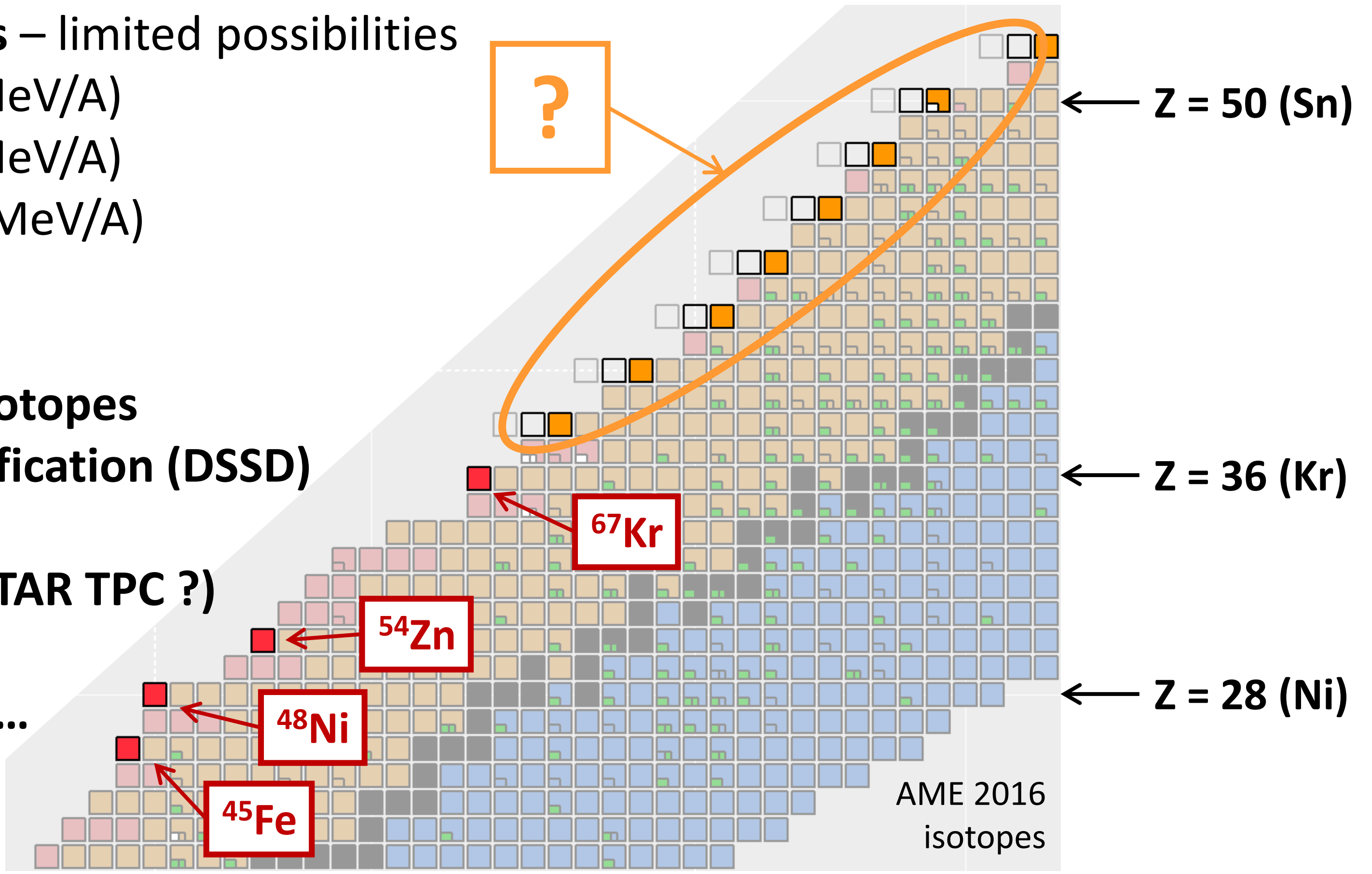
- **theoretical comparison**
  mixing structure model (amplitudes) and 3-body dynamics (decay width)
  - good agreement for **^{45}Fe** and **^{54}Zn**
  - **disagreement for ^{67}Kr**
    deformation region ? emission process (direct / sequential decay) ?

▶ FAIR / Super-FRS: the ideal facility for 2P radioactivity ?

- **current facilities** – limited possibilities
  - **GANIL** (95 MeV/A)
  - **NSCL** (160 MeV/A)
  - **RIKEN** (350 MeV/A)

- **FRS / Super-FRS**
  - **search for isotopes**
    decay identification (DSSD)
    → DESPEC
  - **tracking (ACTAR TPC ?)**

depends on beams…
availability ?
intensities ?



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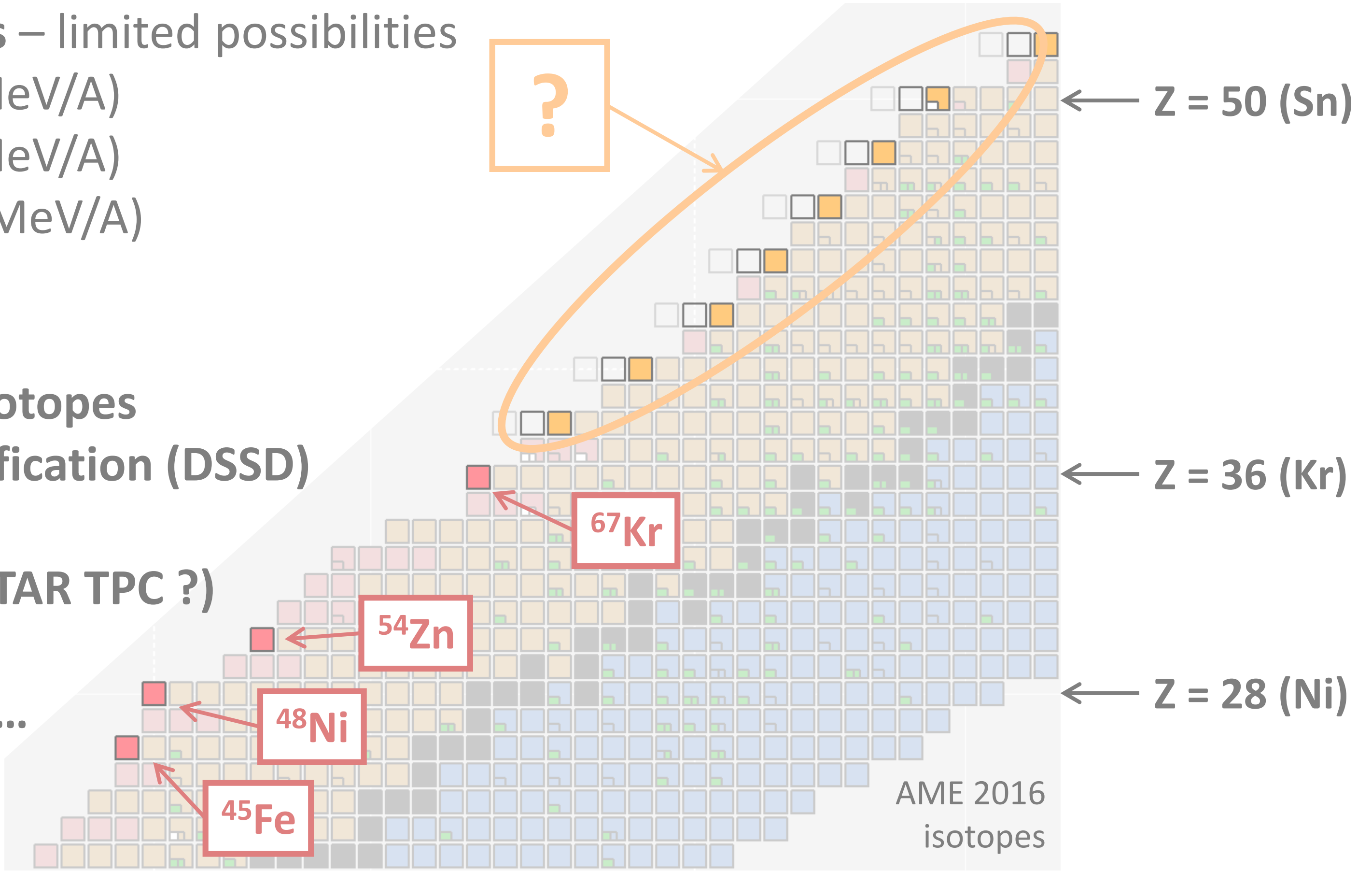

- **search for 2-neutron radioactivity (ex. ^{31}F) ?**
  centrifugal barrier → ground state with large angular momentum

summary of main experimental results

1996	^{45}***Fe*** observation	GSI	**PRL 77**, B. Blank *et al.*
2000	^{48}***Ni*** observation	GANIL	**PRL 84**, B. Blank *et al.*
2002	2P radioactivity (indirect) of ^{45}***Fe***	GANIL	**PRL 89**, J. Giovinazzo *et al.*
2002	2P radioactivity (indirect) of ^{45}***Fe***	GSI	**EPJA 14**, M. Pfützner *et al.*
2005	observation and 2P (indirect) of ^{54}***Zn***	GANIL	**PRL 94**, B. Blank *et al.*
2007	direct obs. of ^{45}***Fe*** 2P decay	GANIL	**PRL 99**, J. Giovinazzo *et al.*
2007	*angular correl. in* ^{45}***Fe*** *2P decay*	*NSCL*	*PRL 99, K. Miernik et al.*
2011	direct obs. of ^{54}***Zn*** 2P decay	GANIL	**PRL 107**, P. Ascher *et al.*
2011	*direct obs. of* ^{48}***Ni*** *2P decay*	*NSCL*	*PRC 83, M. Pomorski et al.*
2016	^{67}***Kr*** observation	RIKEN	**PRC 93**, B. Blank *et al.*
2016	2P radioactivity (indirect) of ^{67}***Kr***	RIKEN	**PRL 117**, T. Goigoux *et al.*

thank you…

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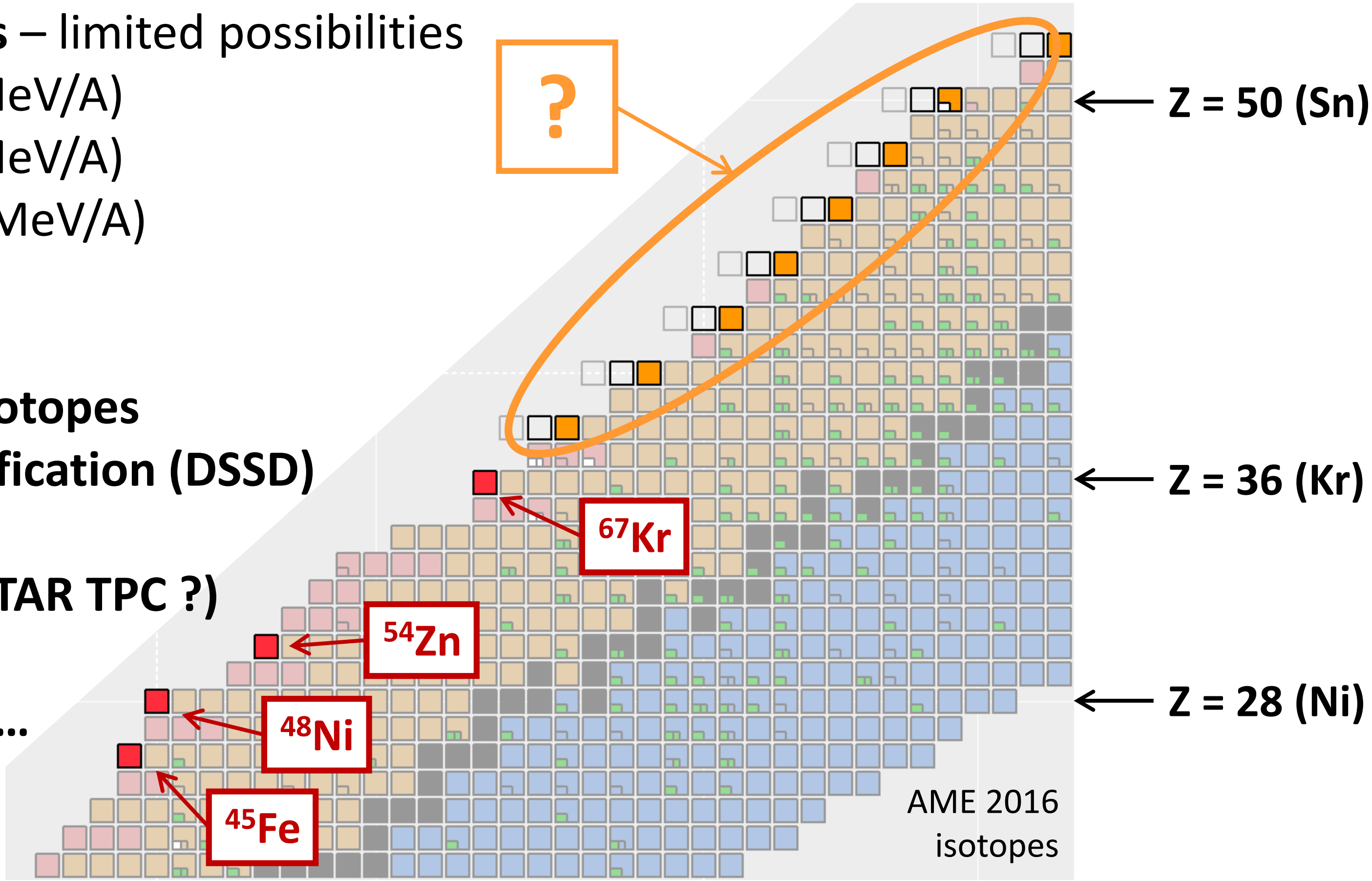
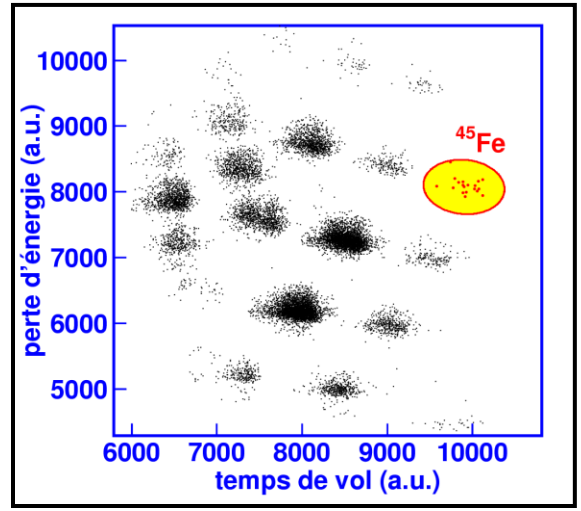


thank you…

^{45}Fe decay: first experiment (GANIL)

identification matrix

→ 22 events for ^{45}Fe



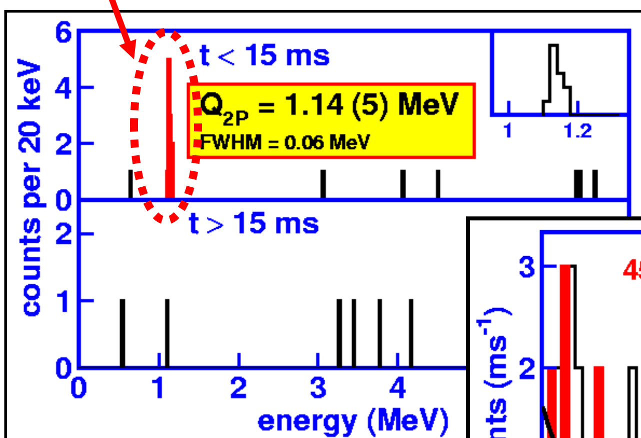
2-proton transition

experimental information: Q_{2P}, $T_{1/2}$

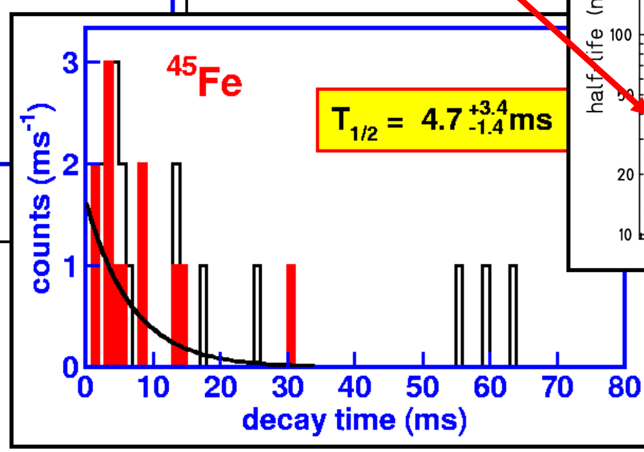
→ **no β coincidence** (>99% C.L.)

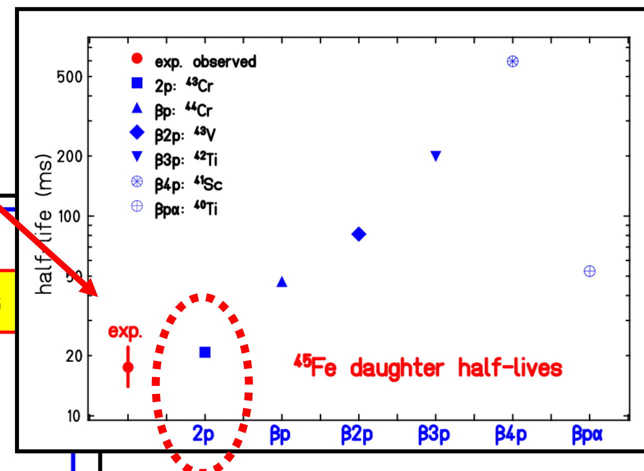
→ **no ΔE_β pile-up** (peak 30% narrower than bp)

→ **daughter decay half-life : ^{43}Cr**



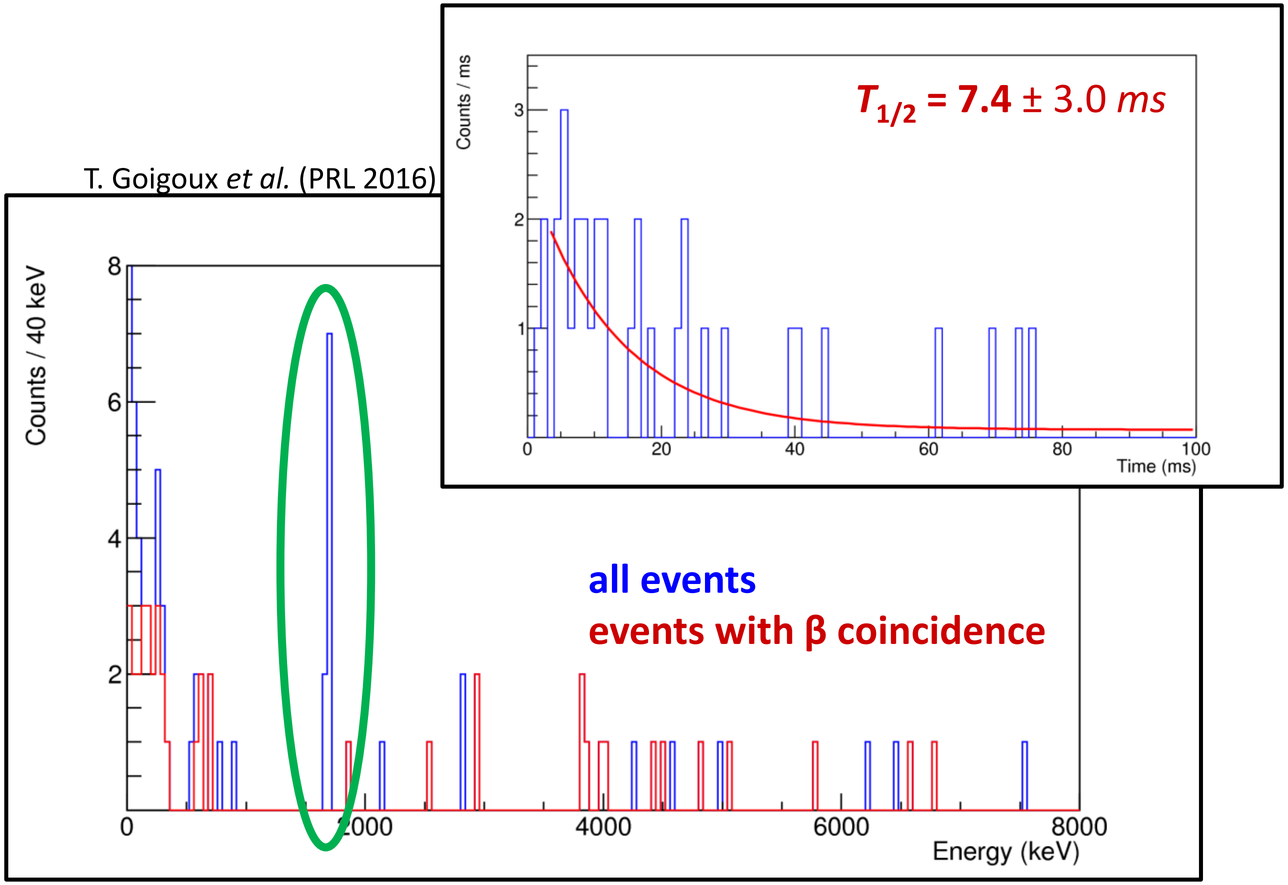
J.G. *et al.* (PRL 2002)





^{67}Kr decay (RIKEN)

T. Goigoux *et al.* (PRL 2016)



observed peak: 9 events
$\boldsymbol{Q_{2P}}$ **= 1.69** ± 0.02 *MeV*

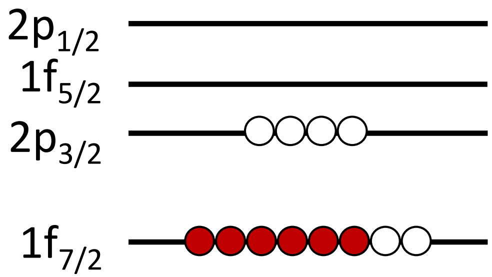
no beta coincidence
$\boldsymbol{\varepsilon_\beta}$ **= 67** %
prob. to miss all ≈ **5×10^{-6}**

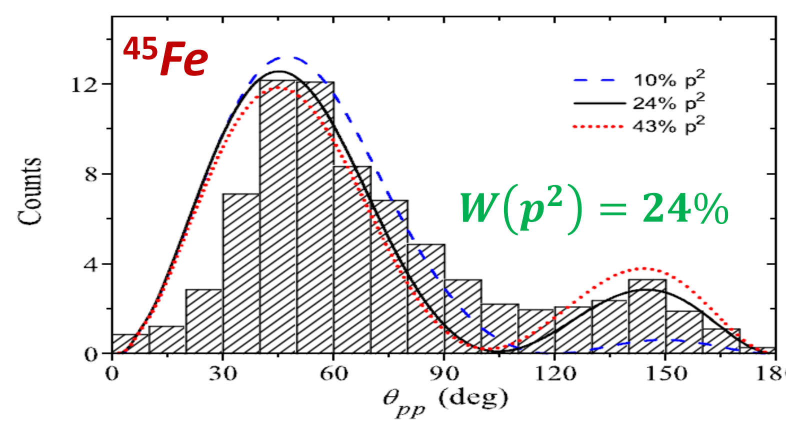
no annihilation 511 *keV*
$\boldsymbol{\varepsilon_\gamma}$ **≈ 8** %
prob. to miss all ≈ **45 %**

Q_{2P} = **1.69** ± 0.02 *MeV*
$T_{1/2}$ = **7.4** ± 3.0 *ms*
BR_{2P} = **37** ± 14 **%**

probing structure beyond the drip-line

^{45}***Fe*** : 26 protons



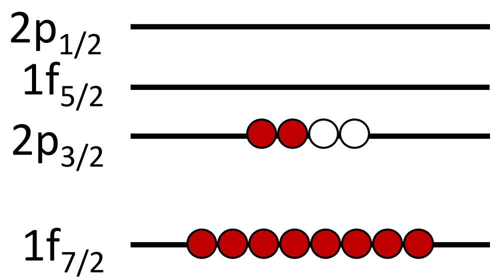


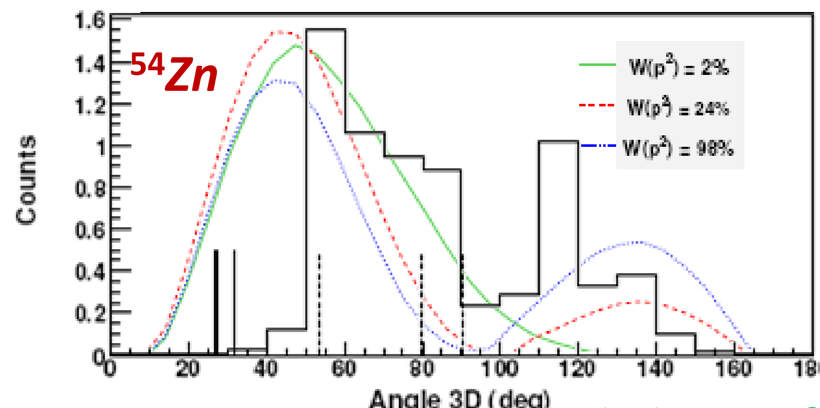
$W(p^2) = 24\%$

K. Miernik *et al.*, EPJA (2009)

^{54}***Zn*** : 30 protons

proton-proton angular distribution → orbitals configuration

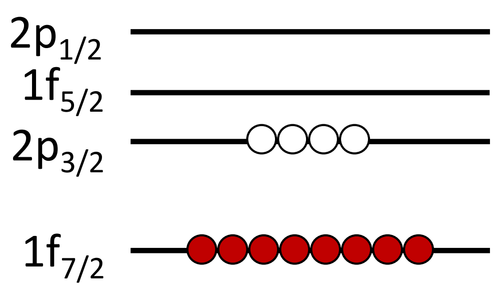




P. Ascher *et al.*, PRL (2011)

$W(p^2) = 30^{+33}_{-21}\%$

^{48}***Ni*** : 28 protons



^{48}***Ni ??***

doubly magic → pure configuration ?

mixing structure and dynamics: half-lives

L.V. Grigorenko: good dynamics
half-lives:
$T_{1/2}$ for pure (s^2,) p^2 and f^2 config.

B.A. Brown: good structure
2-proton amplitudes:
for pure (s^2,) p^2 and f^2 config

"Shell model corrected half-lives"
$A = A(f^2) + A(p^2)$ ⇒ $T_{1/2}$(2P)

	calculation	experiment(s)	
^{45}Fe	2.7 *ms*	$3,76 \pm 0,26$ *ms*	OK
^{54}Zn	1.6 *ms*	$1.98^{+0.73}_{-0.41}$ *ms*	OK
^{67}Kr	660 *ms*	21 ± 12 *ms*	!?

^{67}Kr correlation pattern

On the structure side: region of **deformation**

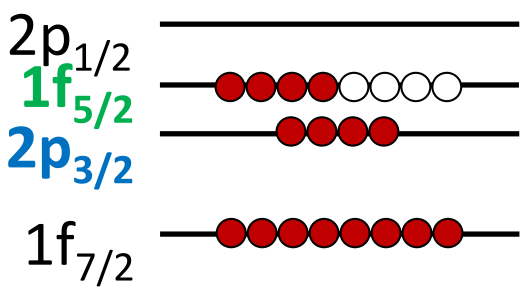
Ongoing work by L.V. Grigorenko *et al*. (revised calculation)

- semi-analytical R-matrix direct decay model
- 3-body model

→ consistent results

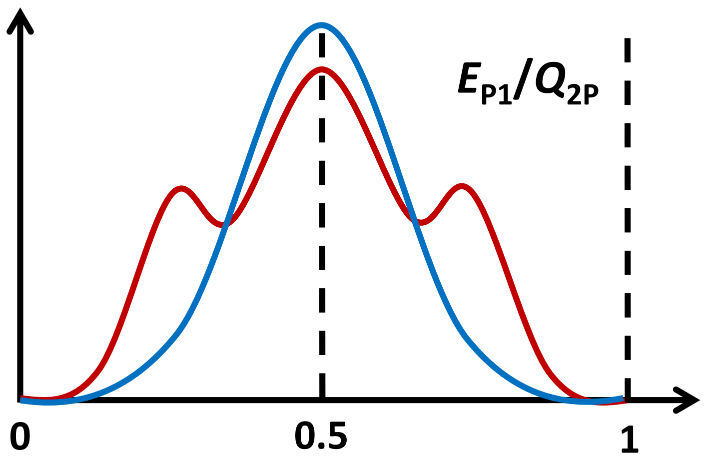
(1) pure $(p_{3/2})^2$ configuration → compatible with exp.
but expected only 18% $(p_{3/2})^2$ config. from shell model

(2) possible interpretation
- possible transition from **2P** to **sequential** decay
- depends on the resonance energy (intermediate state)
- based on S_P ($-400 < S_P < 200$ *keV*) and S_{2P} analysis

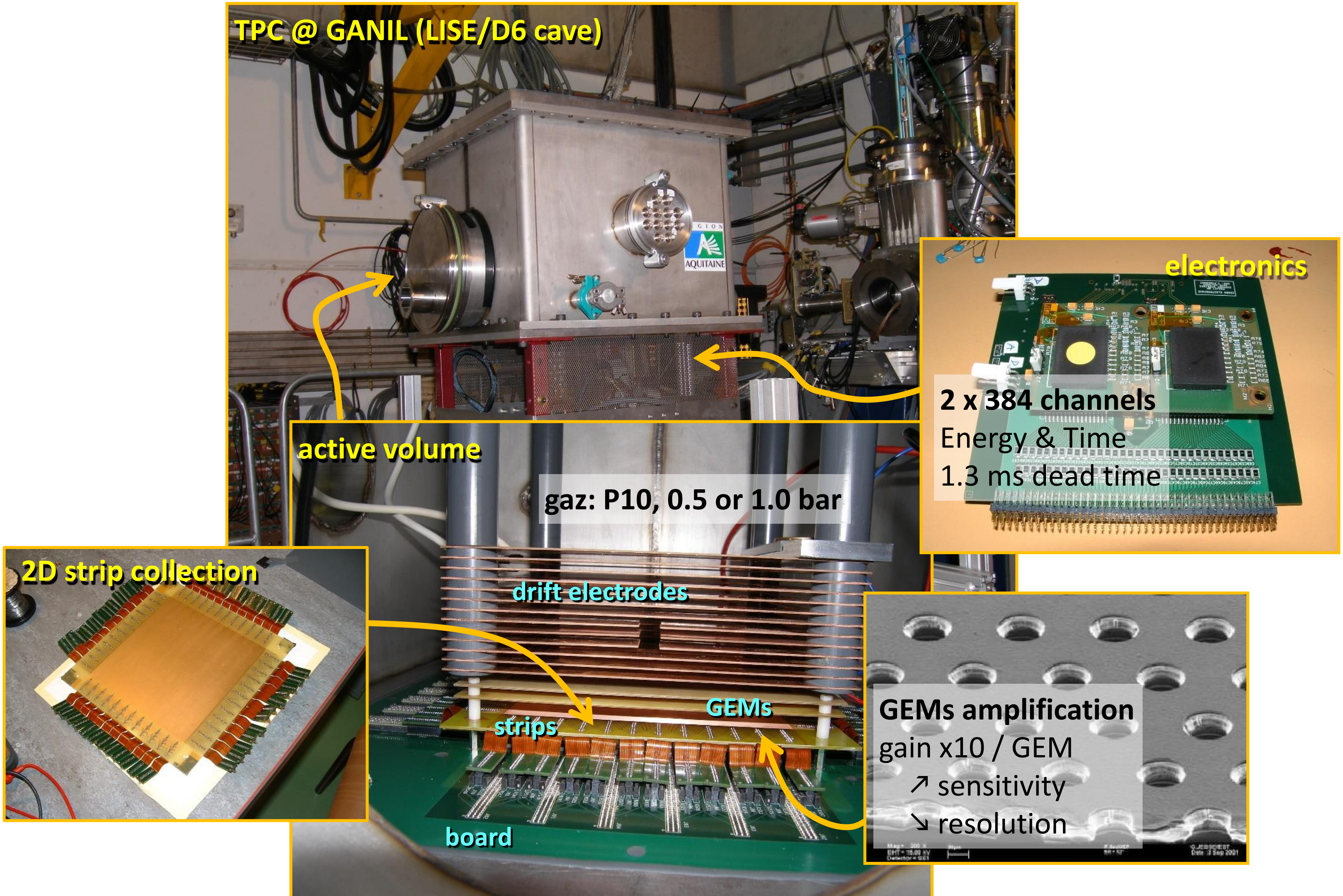


→ **proton-proton correlations**
- no indication available concerning angular correlations
- different **energy sharing** distribution

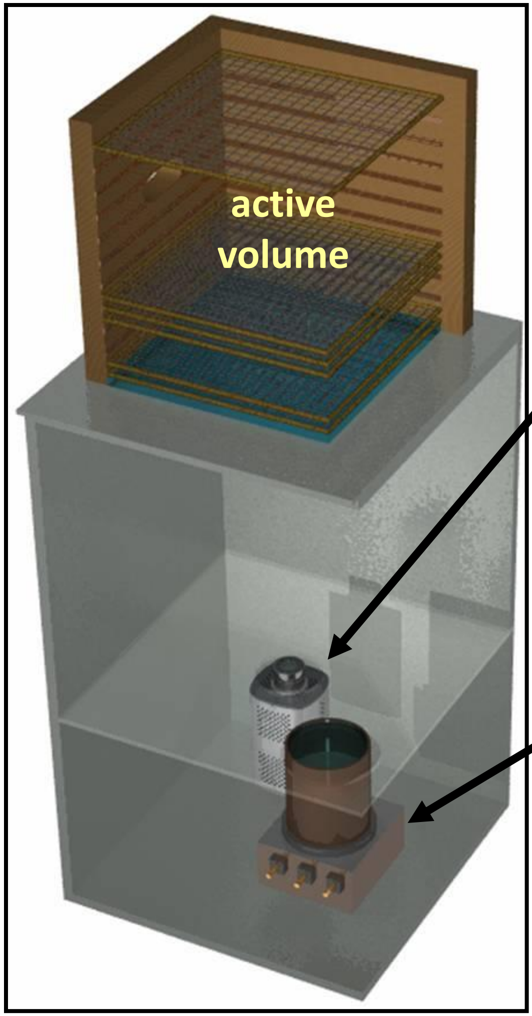
→ **clarify the decay process !!!**



CENBG TPC layout

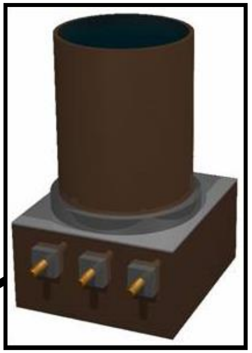


optical TPC from Warsaw team



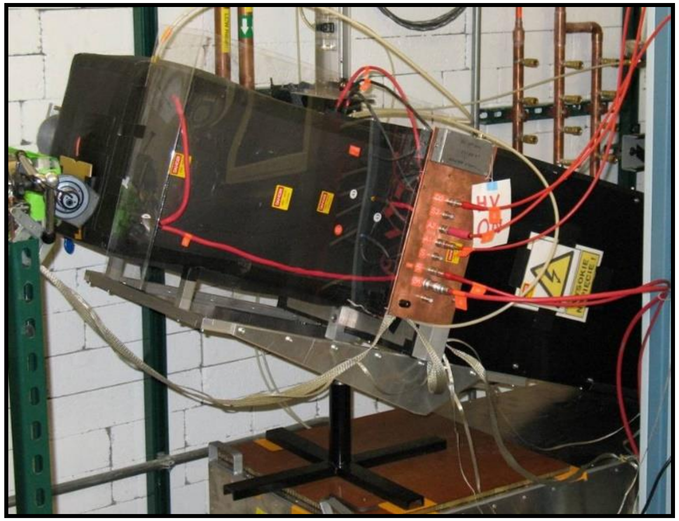
M. Pfützner, K. Miermik, et al., 2007

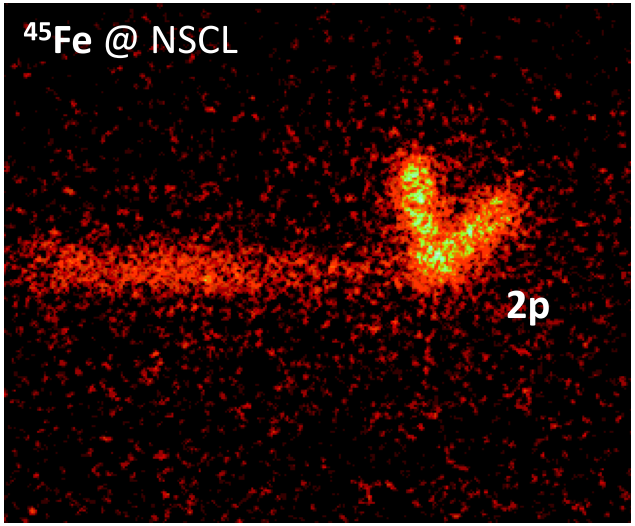
CCD camera
cumulated light



Photomultiplier
with sampling ADC
→ **time** distribution
of signal

K. Miernik *et al.*

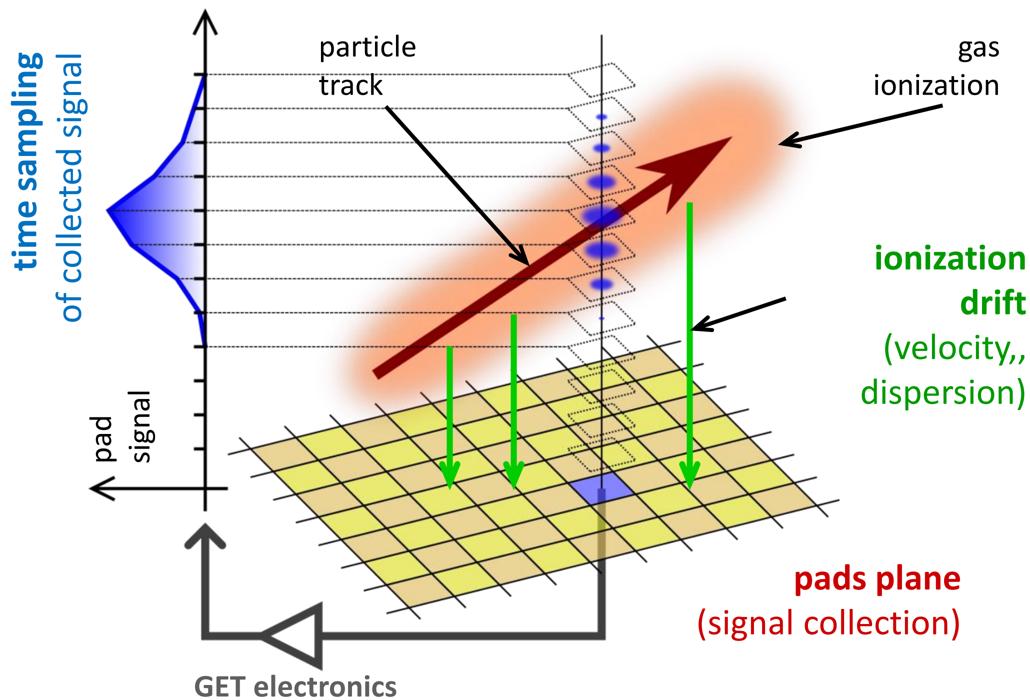


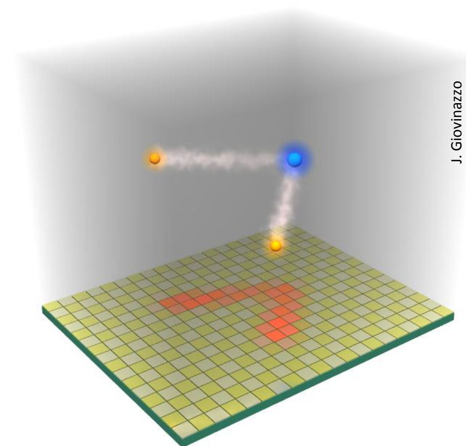


ACTAR TPC principle: full 3D + energy

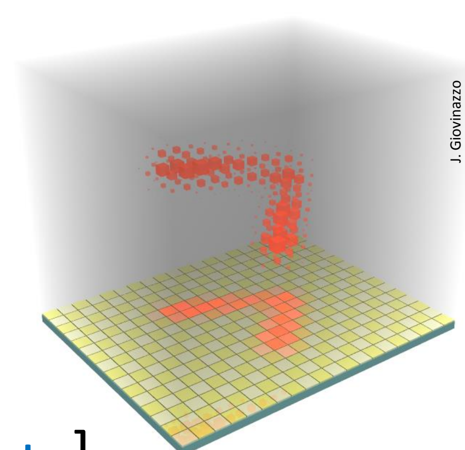
pads plane	TPC principle	time sampling of signal
(signal collection)		
2D digitization	$z \Leftrightarrow t$	3D digitization

$$DE(x,y,z) \Longleftrightarrow DE[x_i,y_j](z) \Longleftrightarrow DE[x_i,y_j](t) \Longleftrightarrow DE[x_i,y_j,t_k]$$





3D reconstruction of ionizations charges along the particles trajectories

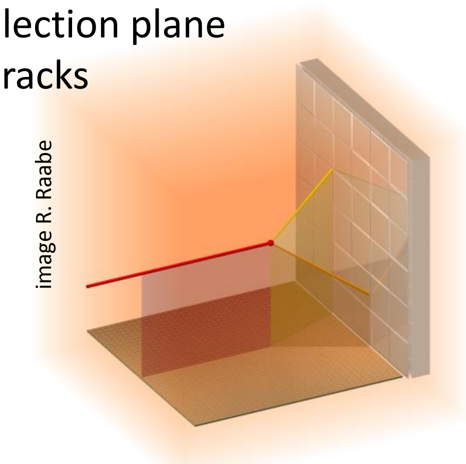


DE[16384 pads × 512 time samples]

1 development, 2 detectors

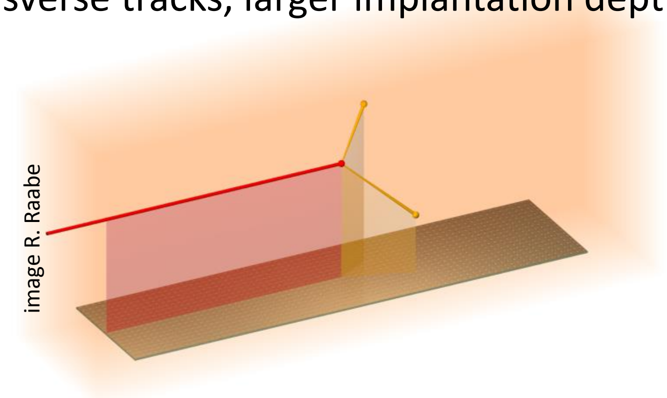
"reaction" chamber

128x128 pads collection plane
large transverse tracks



"decay" chamber

256x64 pads collection plane
short transverse tracks, larger implantation depth



shared design and technology

16384 pads, 2x2 mm^2
2 geometries

→ main funding: ERC
(J.F. Grinyer, GANIL)

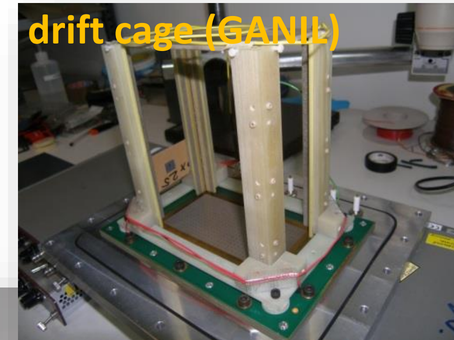
→ decay chamber: Region
pad plane R&D
(J. Giovinazzo, CENBG)

GET electronics
technical solution
for channels readout

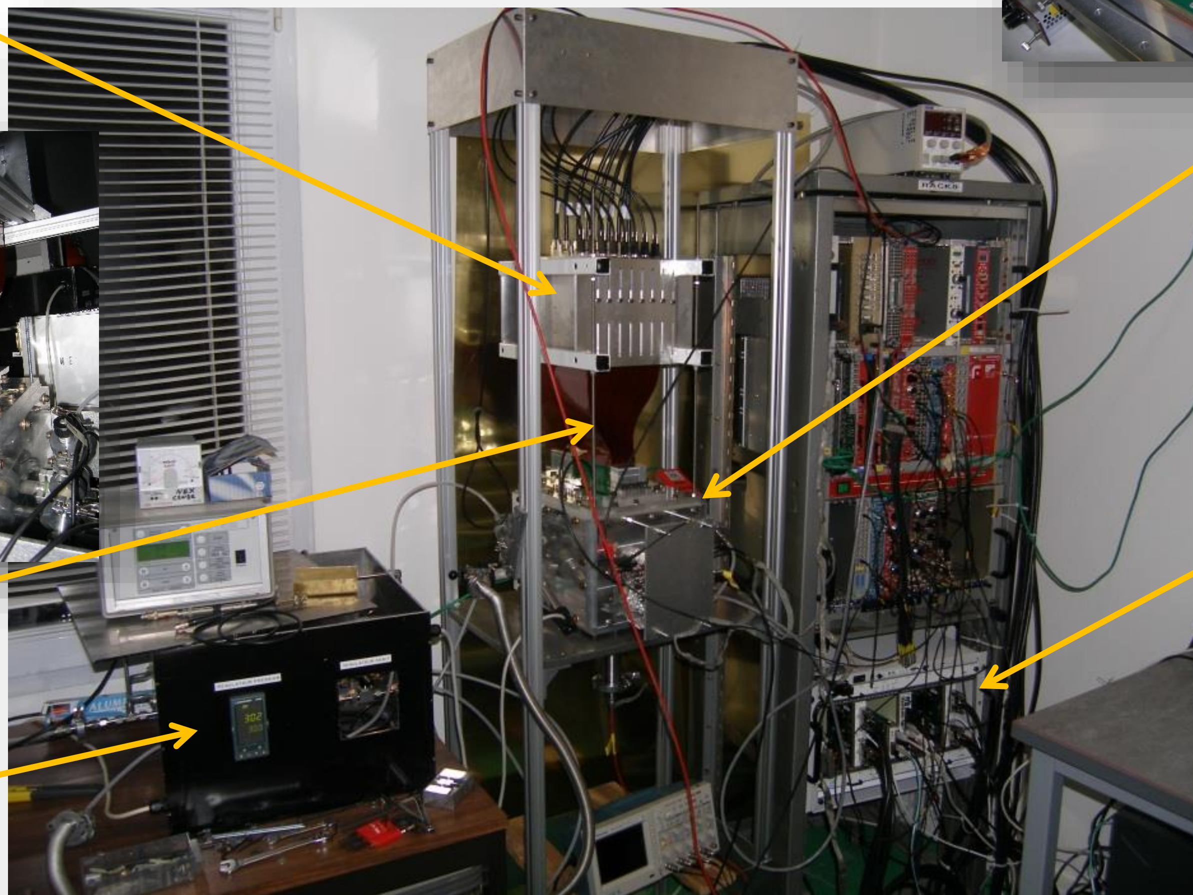
ACTAR TPC demonstrator

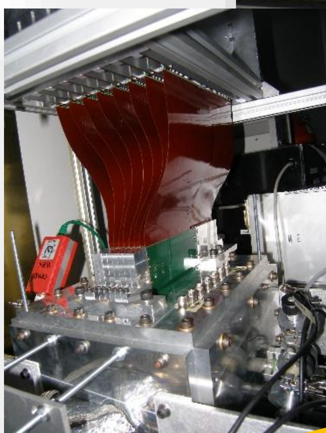
(CENBG version)

full electronics (march 2016) → 2048 pads signal



8 AsAd boards





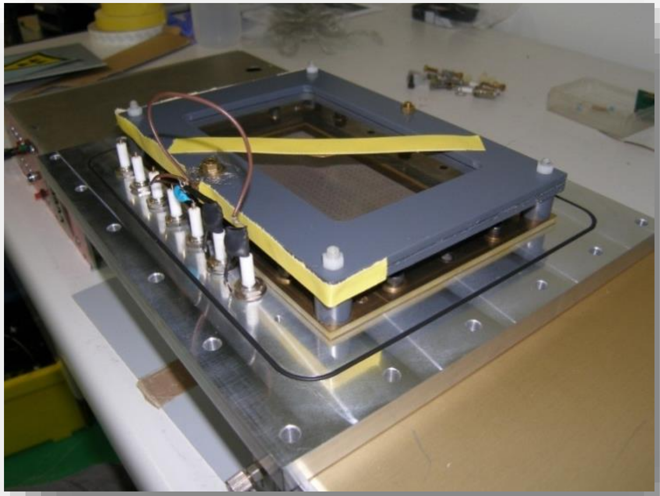
ZAP

demonstrator chamber

µTCA crate CoBo modules

gas control

^{55}Fe X-rays source tests

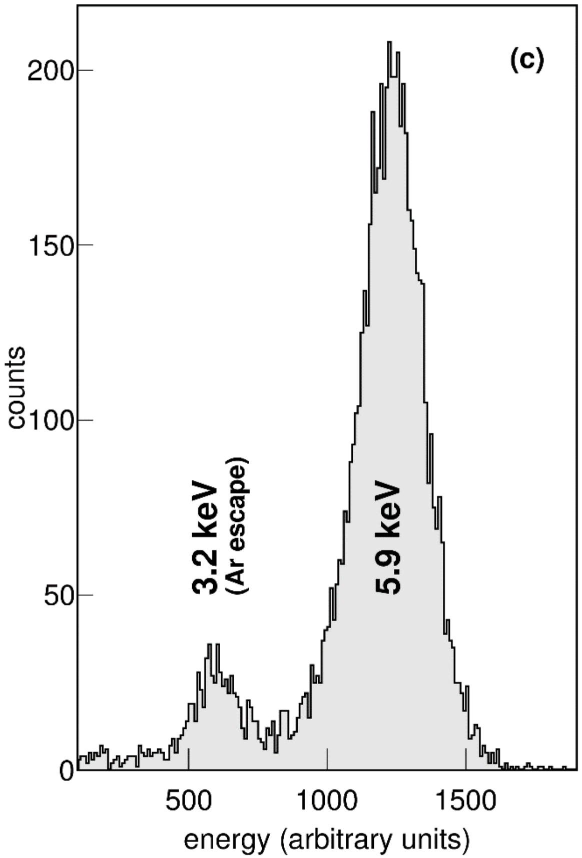


drift volume thickness: **2.5 *cm***

HV_{mesh} = **–570** *V*

HV_{drift} = **–1000** *V*

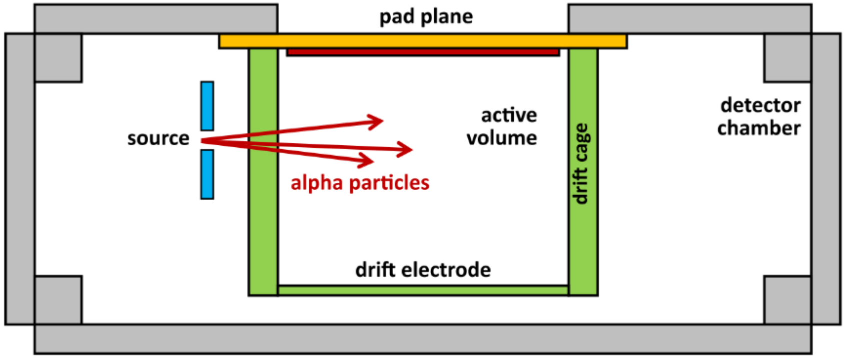
P10 gas (Ar-CH_4), 1 atm

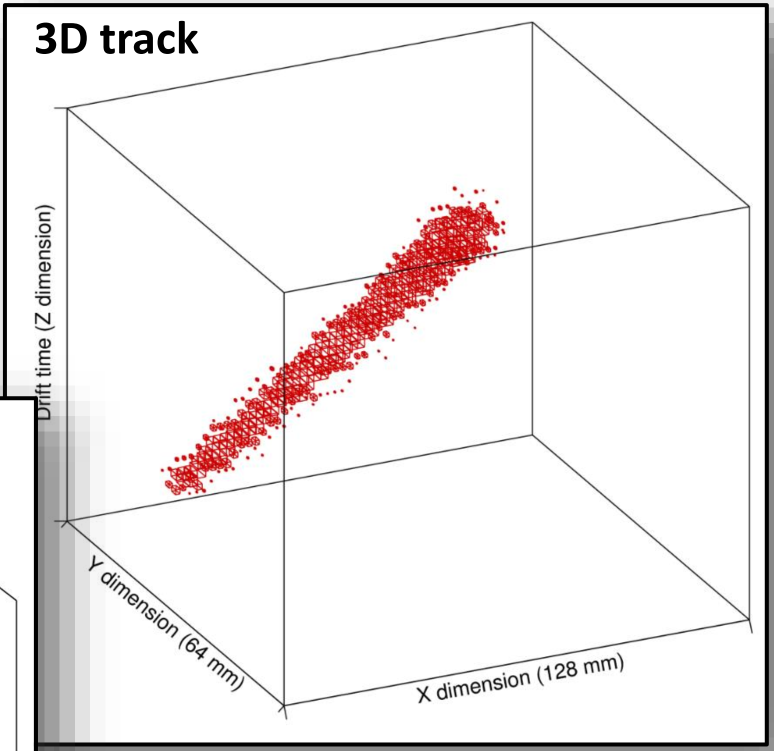


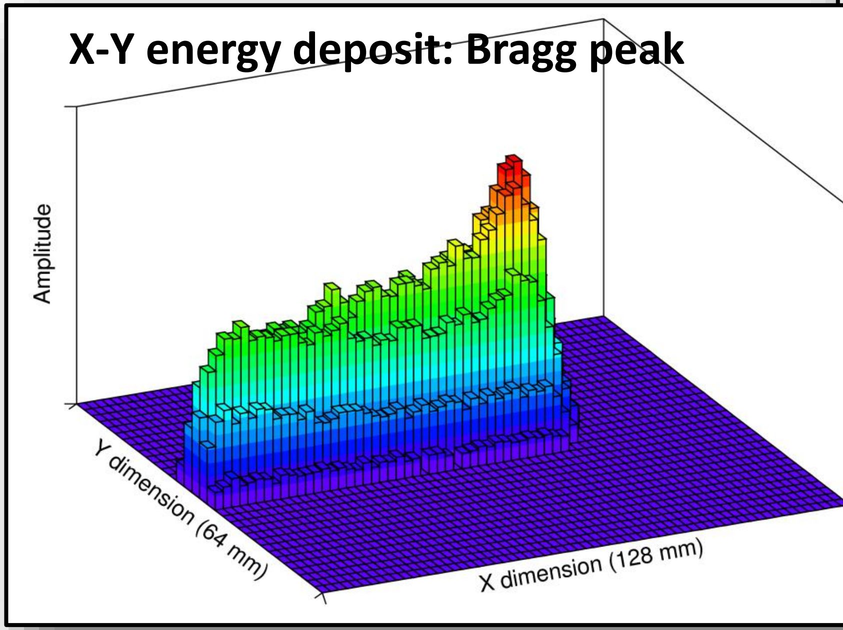
energy resolution (FWHM)
@ **6** *keV*: ~**21 %**

signal from *micromegas* **mesh**
or from **pads**

alpha source tests





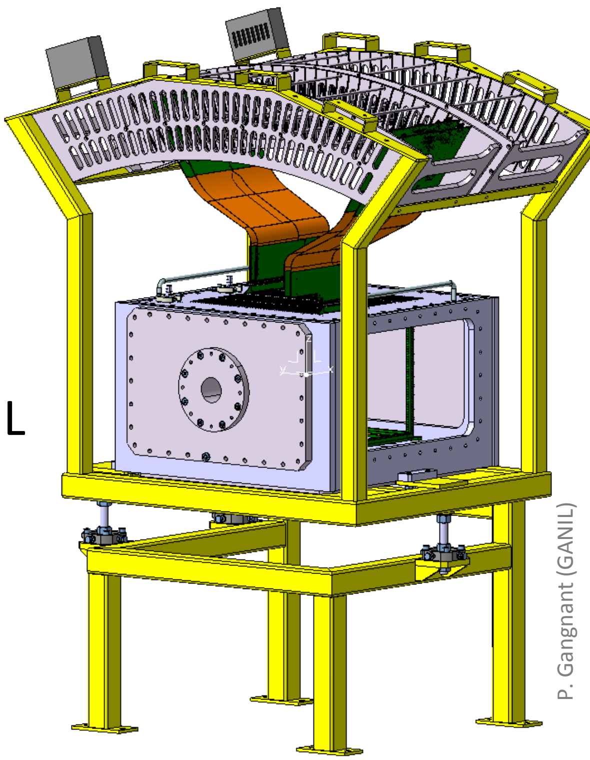


P10 gas (Ar-CH_4), 400 *mbar*

ACTAR TPC current status

pad plane: “CENBG” option selected

electronics: almost ready (few adjustments)

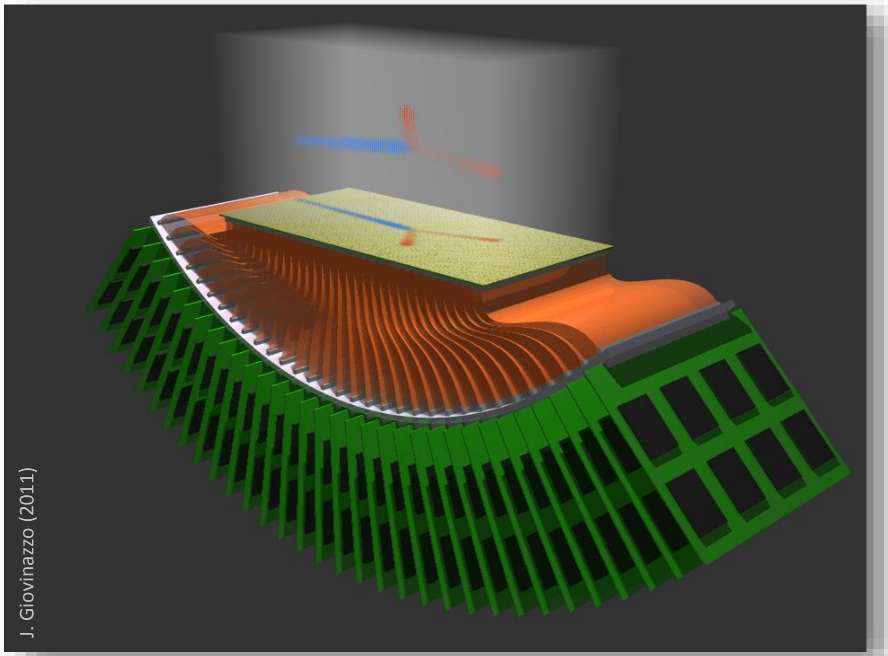


“reaction” detector

under construction at GANIL

→ ready mid 2017

→ first experiment 2018



“decay” detector

final design under study (CENBG)

→ ready mid 2017

→ exp.: GANIL 2018 / RIKEN 2018-2019